Uncertainty-based Adaptive AXBT Sampling with SPOTS

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Abstract - Naval operations continue to evolve toward Littoral Warfare as military action shifts to regional conflicts. To accomplish this evolution, new navigation, sensor, and data-analysis capabilities are needed to support operations in the highly variable and complicated near-shore waters of the littoral environment. Antisubmarine Warfare (ASW) is often conducted in shallow-water areas, where subsurface enemies pose a constant threat, and where knowledge of ocean thermal data is critical, but lacking. Planning operations in these harsh-environment areas is difficult because accurate predictions of sensor performance depend on detailed knowledge of the local conditions. Tactical mission planning is thus seldom optimal or efficient, often resulting in coverage gaps and increased risk.

The Naval Air Systems Command has recently been exploring new environmental sonobuoy concepts to better characterize the littoral environment. Most designs contain a thermistor string, to measure ocean temperatures, and other environmental sensors. This type of sonobuoy, with a complex set of sensors, would be more expensive than a traditional AXBT but it could provide a more thorough littoral environment assessment. The increased cost implies the need for an Environmental Decision Aid to determine the minimum number and best locations for sensors to meet performance objectives. The work reported here concerns the development and evaluation of Sensor Placement for Optimal Temperature Sampling (SPOTS), which addresses these sampling requirements.

The SPOTS process follows the following steps: 1) divide the area of interest into cells with varying volumes of water; 2) estimate the volume-weighted uncertainty of temperatures and the local anisotropic temperature covariance in each cell, based on current optimal interpolation nowcasts; 3) calculate the overall volume-weighted reduction in temperature uncertainty that would result from various sampling patterns; and 4) choose the pattern with the lowest uncertainty. This uncertainty-based approach leads to sampling patterns that produce the highest accuracy temperature characterizations.

SPOTS employs three innovations: 1) analysis of remotely-sensed data, confirmed with a numerical model, when needed; 2) adapting the covariance ellipse axes automatically to the predominant coastline features; and 3) using depth-weighted and volume-weighted uncertainty where the depth-dependent uncertainty and volume of water in a cell is considered in the optimization process. SPOTS uses an optimal interpolation technique that weights all input data by their uncertainties and provides uncertainty estimates for the output. That is a significant advantage over other interpolation schemes. Horizontal/vertical smoothing routines remove large discontinuities and produce the final "nowcast." As a result of these innovations, SPOTS sampling recommendations emphasize the upper water column, where most of the dynamic effects occur, and where acoustic variability is greatest.

Data from several water-sampling flights in the Sea of Japan off the east coast of Korea were used to develop SPOTS. Approximately 44 AXBTs were dropped on a 15-min grid during each flight. Ten combinations of these AXBT measurements, ranging from three to all of the measurements, were assimilated into the Modular Ocean Data Assimilation System (MODAS). The climatology alone and climatology with assimilated satellite sea surface temperatures brought the number of cases to twelve. These were analyzed to determine the relationship between nowcast accuracy and the number (and placement) of assimilated in-situ measurements. The sub-sampled nowcast estimates were compared with the measured temperatures and reported as RMS temperature errors. The results show that: 1) a small number of well-placed measurements outperforms a larger number of gridded measurements; 2) a small number of poorly-placed measurements can significantly degrade a nowcast; and 3) approximately 3-5 measurements per 10,000 nmi^2 are required to reduce RMS temperature errors by 50% compared to climatology.

I. INTRODUCTION

Naval operations continue to evolve toward Littoral Warfare as military action shifts to regional conflicts. To accomplish this evolution, new navigation, sensor, and data-analysis capabilities are needed to support operations in the highly variable and complicated near-shore waters of the littoral environment. Antisubmarine Warfare (ASW) is often conducted in shallow-water areas, where subsurface enemies pose a constant threat, and where knowledge of ocean thermal data is critical but lacking. Planning operations in these harsh-environment areas is difficult because accurate predictions of sensor performance depend on detailed knowledge of the local conditions. Tactical mission planning is thus seldom optimal or efficient, often resulting in coverage gaps and increased risk. According to the Navy's Tactical Acoustics Measurement and Decision Aid Mission Need Statement, "*Air ASW tactical execution, especially in littoral seas, requires in-situ environmental updates for preflight mission planning. In the conduct of ASW operations, an urgent need for explicit*

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knowledge of environmental variables is required to optimize the effectiveness of operational acoustic sensors, as well as acoustic sensors in development."

The Naval Air Systems Command has considered new ways to better characterize the littoral environment. One possibility is a new or upgraded extended-life sonobuoy with thermistors to measure ocean temperatures while drifting through an area. A new capability, like this, would be more expensive than a traditional AXBT (Airborne eXpendable BathyThermograph) temperature sensor but it would provide valuable additional data for littoral environmental characterization. The increased cost drives the need for an environmental decision aid to determine the minimum number and optimal locations of environmental buoys to meet performance objectives. The November 2007 Requirements Document from the Naval Oceanographic Office (NAVO) states in Sec. 1 *"Sampling guidance: Development of guidance on the best way to deploy, spatially and temporally, observation systems in order to meet various forecasting, model assimilation, and model evaluation objectives is needed."* This paper describes a new sampling scheme called SPOTS (Sensor Placement for Optimal Temperature Sampling) that addresses these Navy requirements. We also demonstrate how improved environmental descriptions directly lead to improved ASW search tactics that exploit detailed temperature structures.

Problems with current thermal-sampling approaches include: 1) the requirement for excessive measurements; 2) the need for too much time on station for environmental assessment; and 3) insufficient temperature accuracy/resolution. The non-adaptive random and structured nature of operational sampling is a major deficiency. Other deficiencies include: 1) the inability of mission planners to match viable mission planning solutions to operational requirements and 2) the use of the Rossby radius default for covariance distance, which is suspect in littoral waters. *SPOTS includes new adaptive techniques to reduce sampling randomness and uncertainty and increase accuracy and efficiency.*

II. NEW APPROACH

SPOTS is a new ocean sampling scheme that produces intelligent sensor deployment patterns by analyzing the environmental uncertainty applicable on a given day in the area of interest, and then clusters sensors appropriately. This space/time adaptive approach results in fewer environmental measurements, less time "on-station" for environmental work, and increased temperature accuracy and resolution. Temperature fields, in the form of nowcasts, are created with data assimilated from optimally placed in-situ sensors. SPOTS can optimize AXBT placement in the near-term and will be applicable to optimize glider tracks in the longer-term. An example set of sampled temperature fields showing disparate results follows.

Fig. 1 is an example that illustrates the need for and value of SPOTS. It shows four versions of ocean temperature nowcasts at 50-m depth (blue = colder and red = warmer) in the Sea of Japan (gray = Korea) during a summer experiment.

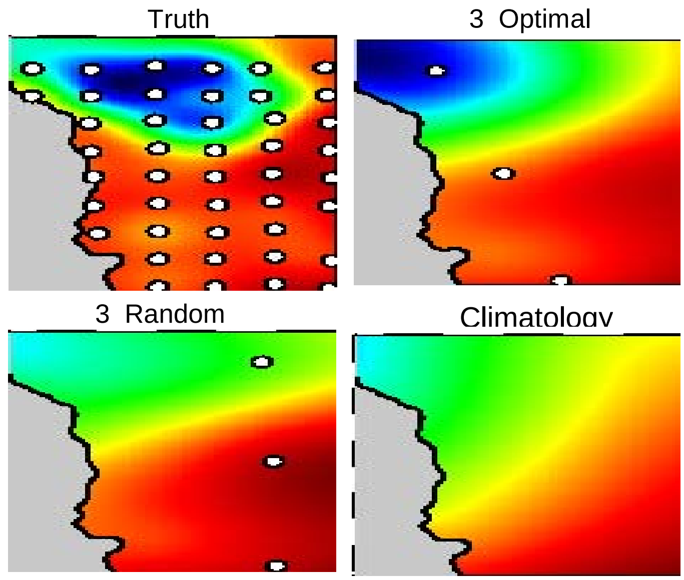

Figure 1. Example AXBT sampling patterns and resultant temperature fields.

The upper left image shows the resulting nowcast after a 6-hr water-sampling mission with 44 AXBTs (drop locations shown). The northern cold-water-core is clearly defined in this over-sampled situation. The lower right image shows standard smooth climatology with little definition. The lower left image shows the result of dropping one set of 3 AXBTs. This result is not much better than climatology and is far from the true conditions. This AXBT sampling pattern would lead to extremely inaccurate tactical acoustic predictions. The upper right image shows a different set of 3 AXBTs that provides a good temperature characterization with reasonable general structure, and also the cold core. This sparse, 3 AXBT sampling pattern, would provide very good temperature structure for tactical sonar planning. The goal of SPOTS is to find the minimum number and optimal locations of sensors that would adequately describe actual conditions.

The SPOTS process follows: 1) divide the area of interest into cells with varying volumes of water; 2) estimate the volume-weighted uncertainty of temperatures and the local anisotropic temperature covariance in each cell based on current optimal interpolation nowcasts from NAVO; 3) calculate the overall volume-weighted reduction in temperature uncertainty that would result from various sampling patterns; and 4) choose the pattern with the lowest uncertainty. Our previous work has shown that this uncertainty-based approach leads to sampling patterns that produce the highest accuracy temperature characterizations.

SPOTS employs three innovations focused on the above problem: 1) analysis of remotely-sensed data, confirmed with a numerical model, when needed; 2) adapting the covariance ellipse axes automatically to the predominant coastline features; and 3) using depth-weighted and volume-weighted uncertainty, where the depth-dependent uncertainty and volume of water in a cell is considered in the optimization process. We use an optimal interpolation technique that

weights all input data by their uncertainties and provides uncertainty estimates for the output. This technique provides a significant advantage over other interpolation schemes. Horizontal and vertical smoothing routines remove large discontinuities and produce the final "nowcast." As a result of these innovations, SPOTS sampling recommendations emphasize the upper part of the water column, where most of the dynamic effects occur, and where acoustic variability is most affected.

III. APPLICATION

The SPOTS algorithms were applied to the summer Sea of Japan data shown in Fig. 1 for several AXBT sampling densities. The results are shown in Figs. 2-4. Fig. 2 shows the reduction in volume-weighted temperature uncertainty achieved with SPOTS sampling. The uncertainty is calculated as one standard deviation around the mean temperature. The left column shows the values before in-situ measurements. The second through fifth columns show the results after assimilation of 1, 3, 5, and 7 AXBTs, respectively.

The red areas along the coast represent high (1.8 deg C) uncertainty due to coastal currents and small-scale dynamics. The second column shows that if only one AXBT is available, it should be located in the red-orange area near the coast just north of 36 deg N. That site is marked with a star. The new uncertainty at the data site is reduced to the calibration error of the sensor and the surrounding uncertainties are reduced proportionally to their distances from the measurement according to the size of the covariance ellipse used in the assimilation. The SPOTS location gives the maximum reduction in overall volume-weighted temperature uncertainty.

If three or more AXBTs are available, they should be deployed as shown in the third through fifth columns. In each case, the last measurement is marked with a star. When 7 AXBTs are assimilated, much of the area becomes light blue, *i.e.*, uncertainty approximately 0.5 deg C. The numbers in the lower right of each panel give the average uncertainty across the grid. They are 1.34, 1.19, 0.93, 0.77, and 0.64 deg C for 0, 1, 3, 5, and 7 AXBTs, respectively. The SPOTS algorithms guarantee this monotonic improvement.

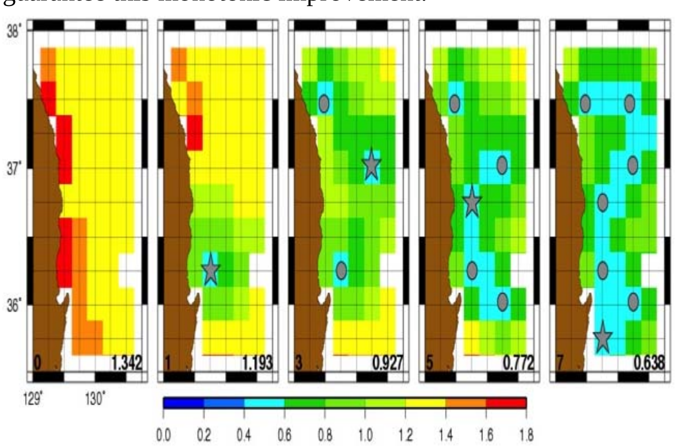

Figure 2. Temperature uncertainty for several AXBT sampling strategies in the Sea of Japan during summer, resulting from SPOTS.

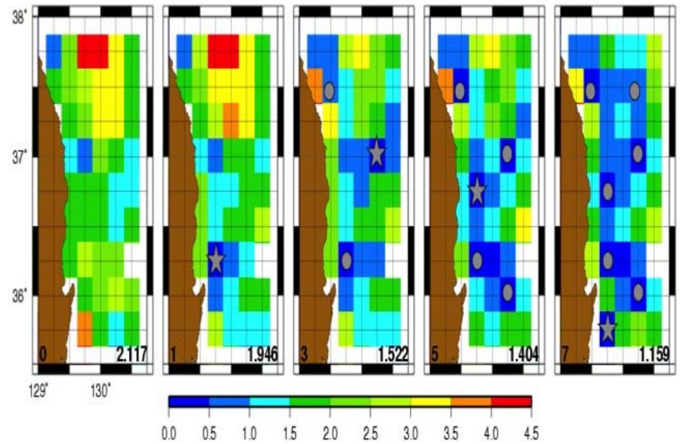

Figure 3. RMS temperature error for several AXBT sampling strategies in the Sea of Japan during summer, resulting from SPOTS.

It is obvious that synoptic measurements with good sensors will reduce uncertainty, as shown in Fig. 2; however, it is not obvious, or even guaranteed, that assimilated measurements will improve a nowcast accuracy. In general, it is not possible to know if, or by how much, nowcast temperature errors have been reduced. But in this case it is possible because we also have the 44 AXBT result to use as a surrogate for ground-truth. For each sampling case we also calculate the RMS difference between the sub-sampled nowcasts and the 44 AXBT "ground-truth" data points.

These results are shown in Fig. 3, where the highest absolute errors (just south of 38 deg N in red) are about 4 deg C before sampling (left column). This error field is unknown, in general, and therefore not available to guide a SPOTS location. The first uncertainty-driven location (second column), just above 36 deg N, reduces errors around the measurement site but does not affect the nowcast in the far north of the area. With three SPOTS AXBTs (third column) there is a significant error reduction throughout the area, including in the far north. The numbers in the lower right of each panel give the average RMS error across the grid. They are 2.12, 1.95, 1.52, 1.40, and 1.16 deg C for 0, 1, 3, 5, and 7 AXBTs, respectively. In order to reduce the average error to 1.5 deg C, only 3 optimally placed measurements are needed in this summer case. This monotonic improvement is not surprising, but it is not guaranteed by any uncertainty-based approach. In other words, the correlation between uncertainty and accuracy is not guaranteed and the process can make a wrong answer more certain.

One interesting sidelight of the optimal interpolation techniques commonly used in assimilation processes is that small errors can occur locally due to the size of the covariance ellipse. If a measurement indicates a change from an archival or "first-guess" field, that delta-temperature will be spread out around the measurement site according to the spatial (and temporal) covariances that are assumed to be appropriate for the region. If the covariance distance is too large in a local area, then the "delta" will be spread too far. One example of this can be seen in the third column result in Fig. 3 near the

coast at about 37.5 deg N. In the shallow-water (small water volume) coastal cell, the initial error was about 2 deg C. After 3 measurements, that error increased to about 3.5 deg C. However, the regional improvement, from 2.12 to 1.16 deg C, outweighs the small local degradation.

IV. VALIDATION

We developed SPOTS based on the Sea of Japan data given above. For validation, we applied the algorithms to a different data set collected in the Yellow Sea. Fig. 4 shows those results plotted against density of AXBT samples with exact locations determined by SPOTS.

This validation is based on 5 exercises from 1995 to 1996. Two of the exercises were during the summer and three were during the winter. The dates of the exercises are given in the plots. For example, the exercise on July 11, 1995 is denoted as 19950711. The upper graph in Fig. 4 shows the mean uncertainty of the temperature nowcasts as a function of the number of AXBT temperature measurements per 10,000 nmi^2. The tables in the graph give the number of AXBT locations required to achieve 20 and 40 percent uncertainty reductions and the number of observations required to reduce uncertainty to 1.5, 1.25, and 1.0 deg C. Note that that the uncertainty for the summer cases is higher than for the winter cases. This is likely due to larger variations in the mixed layer and thermocline during the summer. The slopes of the curves indicate that the greatest reduction in mean uncertainty occurs with the first 5 SPOTS AXBT measurements. After 5 measurements there is a diminished effect and the improvement is likely not worth the added expenditure of time or resources. Using this type of analysis tool a tactical mission planner could conserve resources without sacrificing environmental accuracy.

The lower graph in Fig. 4 shows the mean RMS error as a function of the AXBT sampling density. The RMS error is the error between the nowcast temperature field and the ground truth temperature field obtained from the assimilation of the maximum number of AXBT measurements. The average error across the study area in the summer is about 2.1 deg C before sampling. It decreases to about 1.6 deg C with 5 optimally placed measurements. The winter errors are much lower: about 1.6 deg C with no sampling and about 1.4 deg C with 5 SPOTS measurements. These winter errors are so low that in many cases no measurements would be needed to support Navy tactical missions. The tables in the graph give the number of observations required to achieve 20 and 40 percent mean RMS error reduction and to achieve reductions in RMS error of 1.5, 1.25, and 1.0 deg C. Only about 3 measurements are needed during summer to reduce the average error to 1.5 deg C. This is the same result that was obtained for the summer Sea of Japan data.

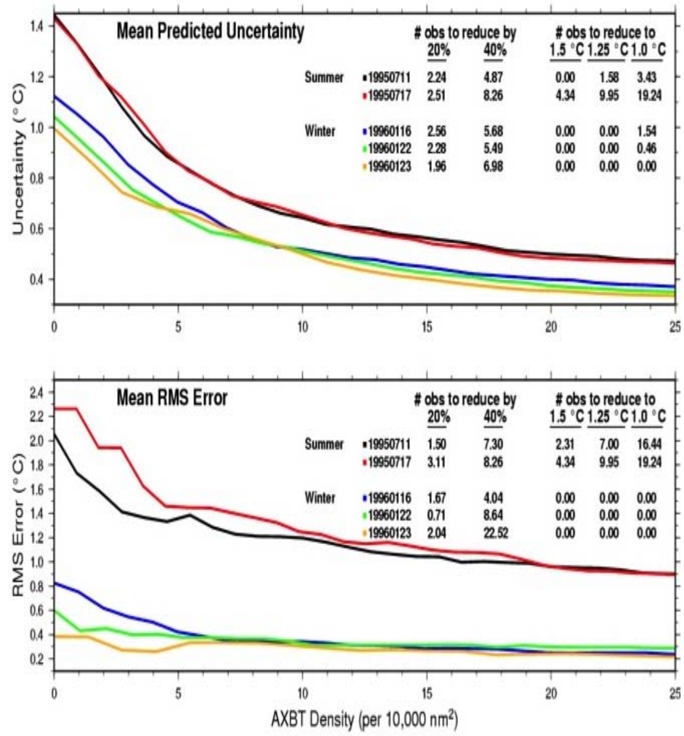

Figure 4. SPOTS validation results in the Yellow Sea.

V. SUMMARY

SPOTS is an environmental decision aid to guide AXBT sampling choices. It is based on the concept of reducing temperature uncertainty, with special emphasis on the local water depth, spatial covariance, and the assumption that uncertainty reduction will often lead to improved accuracy. The analysis shows that placing AXBT sensors at optimal (SPOTS) locations to maximally reduce local temperature uncertainty does indeed reduce the average RMS temperature error (monotonically with increased sampling density) across the region.

This type of analysis provides sampling strategy guidelines that support tactical mission planning. SPOTS calculates the minimum numbers and locations of AXBTs to meet environmental accuracy requirements. For the Sea of Japan and Yellow Sea cases studied, about three optimally placed AXBTs are needed to reduce the average error from over 2 deg C to 1.5 deg C.

If the Navy decides to develop longer-life, drifting environmental sensors for better littoral characterization, the need for an environmental decision for optimal placement will become very important.

ACKNOWLEDGEMENT

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